

Biofiber Reinforcement in Composite Materials

Edited by Omar Faruk and Mohini Sain

Woodhead Publishing Series in Composites Science and Engineering:
Number 51

Biofiber Reinforcement in Composite Materials

Edited by
Omar Faruk and Mohini Sain



AMSTERDAM • BOSTON • CAMBRIDGE • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Woodhead Publishing is an imprint of Elsevier



Woodhead Publishing is an imprint of Elsevier
80 High Street, Sawston, Cambridge, CB22 3HJ, UK
225 Wyman Street, Waltham, MA 02451, USA
Langford Lane, Kidlington, OX5 1GB, UK

Copyright © 2015 Elsevier Ltd. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means electronic, mechanical, photocopying, recording or otherwise without the prior written permission of the publisher.

Permissions may be sought directly from Elsevier's Science & Technology Rights Department in Oxford, UK: phone (+44) (0) 1865 843830; fax (+44) (0) 1865 853333; email: permissions@elsevier.com. Alternatively you can submit your request online by visiting the Elsevier website at <http://elsevier.com/locate/permissions>, and selecting Obtaining permission to use Elsevier material.

Notice

No responsibility is assumed by the publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein. Because of rapid advances in the medical sciences, in particular, independent verification of diagnoses and drug dosages should be made.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Control Number: 2014940871

ISBN 978-1-78242-122-1 (print)

ISBN 978-1-78242-127-6 (online)

For information on all Woodhead Publishing publications visit our website at <http://store.elsevier.com/>

Typeset by Toppan Best-set Premedia Limited

Printed and bound in the United Kingdom



Working together
to grow libraries in
developing countries

www.elsevier.com • www.bookaid.org

Biofiber Reinforcement in Composite Materials

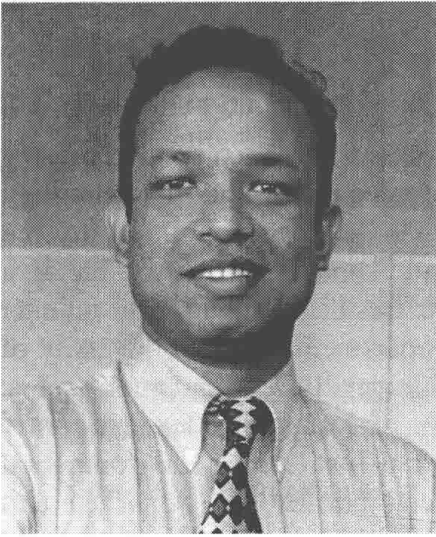
Related titles:

Residual stresses in composite materials
(ISBN 978-0-85709-270-0)

Natural fibre composites
(ISBN 978-0-85709-514-4)

Rehabilitation of metallic civil infrastructure using fiber reinforced polymer (FRP) composites
(ISBN 978-0-85709-653-1)

Dr Omar Faruk



Dr Omar Faruk completed his B.S. and M.S. in Chemistry at the University of Chittagong, Bangladesh. With a DAAD (German Academic Exchange Service) scholarship, he joined at University of Kassel, Germany. He achieved his PhD in Mechanical Engineering at 2005. He worked at the Department of Forestry, Michigan State University, USA as a Visiting Research Associate from 2006 to 2009. Since 2010, he is working at the Centre for Biocomposites and Biomaterials Processing, University of Toronto, Canada. He has more than 70 publications (including a book) to his credit which have been published in different international journals and conferences. He is also an invited reviewer of 48 international reputed journals.

Professor Mohini Sain

Professor Mohini Sain is Dean and professor at Faculty of Forestry, University of Toronto. He specializes in advanced nanocellulose technology, biocomposites and bio-nanocomposites. He is cross-appointed to the Department of Chemical Engineering and Applied Chemistry. He is a fellow of Royal Society of Chemistry, UK. Besides, he is also an adjunct professor of the Chemical Engineering Departments at the University of New Brunswick, Canada; King Abdulaziz University, Jeddah Saudi Arabia; University of Guelph, Canada, University of Lulea, Sweden, Honorary Professor at Slovak Technical University and Institute of Environmental Science at the University of Toronto, and collaborates with American and European research institutes and universities. Prof. Sain holds several awards; the most recent one is the Plastic Innovation Award and KALEV PUGI Award for his innovation and contribution to Industry. Author of more than 300 papers and hi-cited researcher Professor Sain hugely contributed to society at large by translating research to commercialization which led to three new companies making products ranging from packaging to automotive to building construction.

Woodhead Publishing Series in Composites Science and Engineering

- 1 **Thermoplastic aromatic polymer composites**
F. N. Cogswell
- 2 **Design and manufacture of composite structures**
G. C. Eckold
- 3 **Handbook of polymer composites for engineers**
Edited by L. C. Hollaway
- 4 **Optimisation of composite structures design**
A. Miravete
- 5 **Short-fibre polymer composites**
Edited by S. K. De and J. R. White
- 6 **Flow-induced alignment in composite materials**
Edited by T. D. Papathanasiou and D. C. Guell
- 7 **Thermoset resins for composites**
Compiled by Technolex
- 8 **Microstructural characterisation of fibre-reinforced composites**
Edited by J. Summerscales
- 9 **Composite materials**
F. L. Matthews and R. D. Rawlings
- 10 **3-D textile reinforcements in composite materials**
Edited by A. Miravete
- 11 **Pultrusion for engineers**
Edited by T. Starr
- 12 **Impact behaviour of fibre-reinforced composite materials and structures**
Edited by S. R. Reid and G. Zhou
- 13 **Finite element modelling of composite materials and structures**
F. L. Matthews, G. A. O. Davies, D. Hitchings and C. Soutis

- 14 **Mechanical testing of advanced fibre composites**
Edited by G. M. Hodgkinson
- 15 **Integrated design and manufacture using fibre-reinforced polymeric composites**
Edited by M. J. Owen and I. A. Jones
- 16 **Fatigue in composites**
Edited by B. Harris
- 17 **Green composites**
Edited by C. Baillie
- 18 **Multi-scale modelling of composite material systems**
Edited by C. Soutis and P. W. R. Beaumont
- 19 **Lightweight ballistic composites**
Edited by A. Bhatnagar
- 20 **Polymer nanocomposites**
Y-W. Mai and Z-Z. Yu
- 21 **Properties and performance of natural-fibre composite**
Edited by K. Pickering
- 22 **Ageing of composites**
Edited by R. Martin
- 23 **Tribology of natural fiber polymer composites**
N. Chand and M. Fahim
- 24 **Wood-polymer composites**
Edited by K. O. Niska and M. Sain
- 25 **Delamination behaviour of composites**
Edited by S. Sridharan
- 26 **Science and engineering of short fibre reinforced polymer composites**
S-Y. Fu, B. Lauke and Y-M. Mai
- 27 **Failure analysis and fractography of polymer composites**
E. S. Greenhalgh
- 28 **Management, recycling and reuse of waste composites**
Edited by V. Goodship
- 29 **Materials, design and manufacturing for lightweight vehicles**
Edited by P. K. Mallick
- 30 **Fatigue life prediction of composites and composite structures**
Edited by A. P. Vassilopoulos

- 31 **Physical properties and applications of polymer nanocomposites**
Edited by S. C. Tjong and Y-W. Mai
- 32 **Creep and fatigue in polymer matrix composites**
Edited by R. M. Guedes
- 33 **Interface engineering of natural fibre composites for maximum performance**
Edited by N. E. Zafeiropoulos
- 34 **Polymer-carbon nanotube composites**
Edited by T. McNally and P. Pötschke
- 35 **Non-crimp fabric composites: Manufacturing, properties and applications**
Edited by S. V. Lomov
- 36 **Composite reinforcements for optimum performance**
Edited by P. Boisse
- 37 **Polymer matrix composites and technology**
R. Wang, S. Zeng and Y. Zeng
- 38 **Composite joints and connections**
Edited by P. Camanho and L. Tong
- 39 **Machining technology for composite materials**
Edited by H. Hocheng
- 40 **Failure mechanisms in polymer matrix composites**
Edited by P. Robinson, E. S. Greenhalgh and S. Pinho
- 41 **Advances in polymer nanocomposites: Types and applications**
Edited by F. Gao
- 42 **Manufacturing techniques for polymer matrix composites (PMCs)**
Edited by S. Advani and K-T. Hsiao
- 43 **Non-destructive evaluation (NDE) of polymer matrix composites: Techniques and applications**
Edited by V. M. Karbhari
- 44 **Environmentally friendly polymer nanocomposites: Types, processing and properties**
S. S. Ray
- 45 **Advances in ceramic matrix composites**
Edited by I. M. Low

46 **Ceramic nanocomposites**

Edited by R. Banerjee and I. Manna

47 **Natural fibre composites: Materials, processes and properties**

Edited by A. Hodzic and R. Shanks

48 **Residual stresses in composite materials**

Edited by M. Shokrieh

49 **Health and environmental safety of nanomaterials: Polymer nanocomposites and other materials containing nanoparticles**

Edited by J. Njuguna, K. Pielichowski and H. Zhu

50 **Polymer composites in the aerospace industry**

Edited by P. E. Irving and C. Soutis

51 **Biofiber reinforcement in composite materials**

Edited by O. Faruk and M. Sain

52 **Fatigue and fracture of adhesively-bonded composite joints: Behaviour, simulation and modelling**

Edited by A. P. Vassilopoulos

Recent trends such as increasing oil prices, depletion of fossil resources and increasing greenhouse gas emissions have encouraged the development of new biodegradable materials produced from renewable resources. In this respect natural fiber-reinforced polymer composites have been developed to replace synthetic composites. There are more than 1000 species of cellulose plants available in fiber form and a number of them are being investigated as composite reinforcement materials. This is part of an increasing interest in investigating new biofibers from a range of sources (such as petiole bark, rachis, rachilla, spatha, palmyrah, talipot, *Sansevieria cylindrica*, sea grass, coconut tree leaf sheath, vakka, okra, elephant grass, abaca leaf fiber, *Sansevieria rifasciata*, *Phormium tenax*, alfa, piassava, isora, *Sansevieria ehrenbergii*, sunflower stalk flour and *Opuntia ficus indica*). Composites with biofibers as reinforcements have potential applications as low-cost building materials, automobile components and other biomedical applications.

There has been research in biocomposites for well over a decade which has demonstrated such advantages of cellulosic fibers as excellent stiffness and strength. However, this has not led to the hoped-for range of applications because of their drawbacks. One problem is variability in fiber quality due to factors such as variations in plant growth, harvesting and extraction. Problems of interfacial adhesion between biofiber and polymer matrix, moisture absorption and long-term durability (affected by ultraviolet light, temperature, and humidity) are also important issues which needed to be resolved.

In recent years, there have been a number of books published on biofiber-reinforced composites covering general processing, properties, performance criteria and applications. This book focuses specifically on biofibers as reinforcements in composite materials. The main biofibers are sub-categorized based on their origin (Part I Bast fibers, Part II Leaf fibers, Part

III Seed fibers, Part IV Grass, reed and cane fibers, and Part V Wood, cellulosic and other fibers including cellulosic nanofibers). Chapters on a specific biofiber review their sources and cultivation, production, fiber properties and modification, integration into matrices, performance and current applications. The book will be helpful to researchers, engineers, chemists, technologists and professionals who would like to know more about the development and potential of natural fiber-reinforced composites.

Omar Faruk and Mohini Sain

Contents

<i>Contributor contact details</i>	<i>xv</i>
<i>Editor biographies</i>	<i>xxi</i>
<i>Woodhead Publishing Series in Composites Science and Engineering</i>	<i>xxiii</i>
<i>Preface</i>	<i>xxvii</i>
Part I Bast fibers	1
1 The use of jute fibers as reinforcements in composites	3
J. A. KHAN, National University of Bangladesh, Bangladesh and M. A. KHAN, Bangladesh Atomic Energy Commission, Bangladesh	
1.1 Introduction	3
1.2 Composition and properties of jute fibers	4
1.3 Processing and properties of grafted jute fibers	7
1.4 Processing and properties of alkali-treated jute fibers	8
1.5 Characterization of jute fibers	10
1.6 Manufacture of jute fiber composites	11
1.7 Preparation and properties of irradiated jute composites	12
1.8 Preparation and properties of oxidized jute composites	15
1.9 Preparation and properties of mercerized jute composites	18
1.10 Preparation and properties of jute composites modified by other processes	20
1.11 Types and properties of hybrid jute composites	24
1.12 Applications of jute composites	26
1.13 Conclusion	29
1.14 References	29
2 The use of flax fibres as reinforcements in composites	35
J. MÜSSIG and K. HAAG, Hochschule Bremen – University of Applied Sciences, Germany	
2.1 Introduction	35
2.2 Key fibre properties	40

2.3	Cultivation and quality issues	48
2.4	Processing as a fibre reinforcement for composites	54
2.5	Integration into the matrix	61
2.6	Assessing the performance of the composites	69
2.7	Applications	73
2.8	Summary: strengths and weaknesses	73
2.9	Future trends	80
2.10	Sources of further information and advice	81
2.11	Acknowledgements	82
2.12	References	82
3	The use of hemp fibres as reinforcements in composites	86
	H. N. DHAKAL and Z. ZHANG, University of Portsmouth, UK	
3.1	Introduction	86
3.2	Hemp fibre	87
3.3	Key fibre properties	89
3.4	Cultivation and quality issues	90
3.5	Processing of hemp as fibre reinforcement for composites	91
3.6	Surface modifications of hemp fibre and their effects on properties	92
3.7	Fibre-matrix interaction	95
3.8	Current applications of hemp fibres	97
3.9	Future trends	99
3.10	Summary	100
3.11	References	101
4	The use of ramie fibers as reinforcements in composites	104
	Y. DU, N. YAN and M. T. KORTSCHOT, University of Toronto, Canada	
4.1	Introduction	104
4.2	Ramie fiber properties	106
4.3	Improving fiber/matrix interfacial bonding	111
4.4	Ramie fiber-reinforced polymer composites	119
4.5	Factors affecting composite mechanical properties	126
4.6	Other studies of ramie fiber-reinforced composites	128
4.7	Applications	131

4.8	Conclusions	133
4.9	References	133
5	The use of kenaf fibers as reinforcements in composites	138
	H. AKIL, M. H. ZAMRI and M. R. OSMAN, University of Sains, Malaysia	
5.1	Introduction	138
5.2	Processing of kenaf fibers	143
5.3	Matrices for kenaf fiber-reinforced composites	148
5.4	Fabrication of kenaf fiber-reinforced composites (KFRC)	149
5.5	Performance of KFRC	150
5.6	Applications of KFRC	153
5.7	Conclusion	157
5.8	References	158
	Part II Leaf fibers	163
6	The use of sisal and henequen fibres as reinforcements in composites	165
	Y. LI and Y. O. SHEN, Tongji University, China	
6.1	Introduction	165
6.2	The microstructures of sisal fibres	167
6.3	The mechanical properties of sisal fibres	170
6.4	Manufacture of sisal fibre-reinforced composites	176
6.5	Mechanical properties of sisal fibre-reinforced composites: interfacial properties	178
6.6	Mechanical properties of sisal fibre-reinforced composites: interlaminar fracture toughness	182
6.7	Mechanical properties of unidirectional sisal fibre-reinforced composites	186
6.8	Effect of fibre twist on the mechanical properties of sisal fibre-reinforced composites	188
6.9	Durability of sisal fibre-reinforced composites: effects of moisture absorption	195
6.10	Effects of ultraviolet (UV) light on the mechanical properties of sisal fibre-reinforced composites	200
6.11	Applications of sisal fibre-reinforced composites	206
6.12	Conclusion and future trends	207
6.13	Acknowledgements	208
6.14	References	208

7	The use of pineapple leaf fibers (PALFS) as reinforcements in composites	211
	A. L. LEÃO, São Paulo State University (UNESP), Brazil, B. M. CHERIAN and S. NARINE, Trent University, Canada, S. F. SOUZA and M. SAIN, University of Toronto, Canada and S. THOMAS, Mahatma Gandhi University, India	
7.1	Introduction	211
7.2	The pineapple plant	213
7.3	Pineapple production	215
7.4	Pineapple culture in Brazil and worldwide	215
7.5	Fiber extraction	216
7.6	Potential of fiber production plant	218
7.7	Fiber properties	220
7.8	Pineapple leaf fiber (PALF)-reinforced polymer composites	222
7.9	Application of pineapple fibers and composites	226
7.10	Conclusions	232
7.11	References and further reading	233
8	The use of banana and abaca fibres as reinforcements in composites	236
	A. A. MAMUN and H. P. HEIM, University of Kassel, Germany, O. FARUK, University of Toronto, Canada and A. K. BLEDZKI, University of Kassel, Germany and West Pomeranian University of Technology, Poland	
8.1	Introduction	236
8.2	Banana and abaca plants and their cultivation	237
8.3	Fibre extraction	239
8.4	Fibre structure and properties	241
8.5	Disadvantages of banana and abaca fibres as reinforcement materials	244
8.6	Surface modification of fibres	246
8.7	Processing of banana/abaca fibre-reinforced composites	250
8.8	Performance of banana/abaca fibre-reinforced thermoset polymer composites	252
8.9	Performance of banana/abaca fibre-reinforced thermoplastic polymer composites	257
8.10	Performance of banana/abaca fibre-reinforced biodegradable polymer composites	267
8.11	Conclusions	269
8.12	References	269